Photovoltaic Power: Science and Technology Fundamentals

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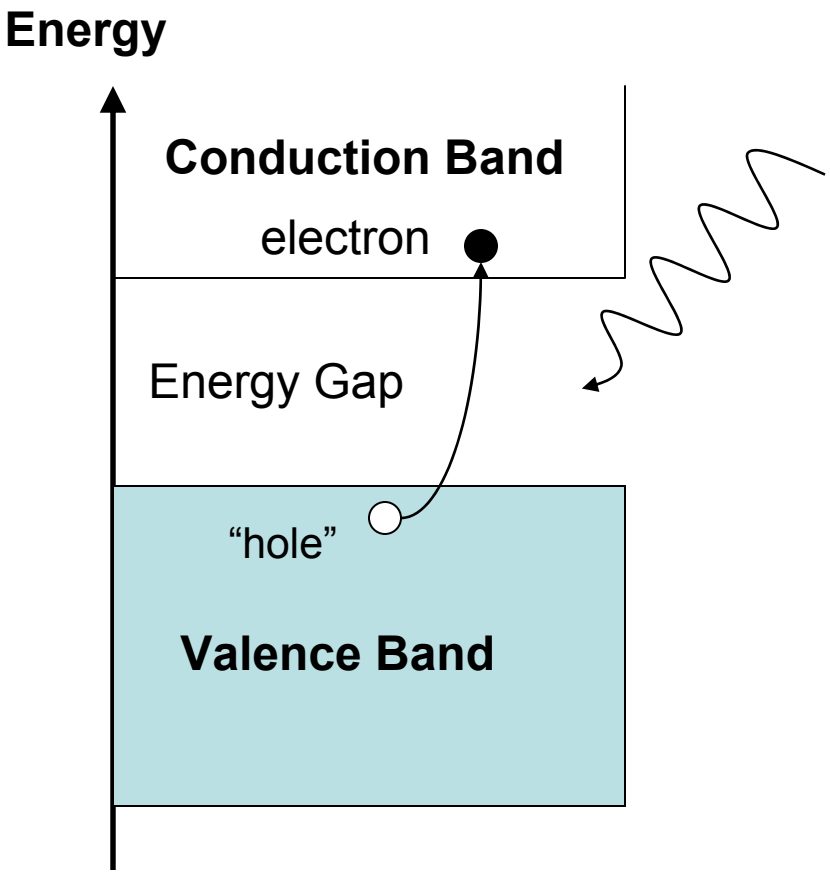
Evergreen Solar, Inc.

Renewable Energy Seminar, Nov. 2, 2006

Photovoltaic Principle



Semiconductor band model

Light in, electrons out

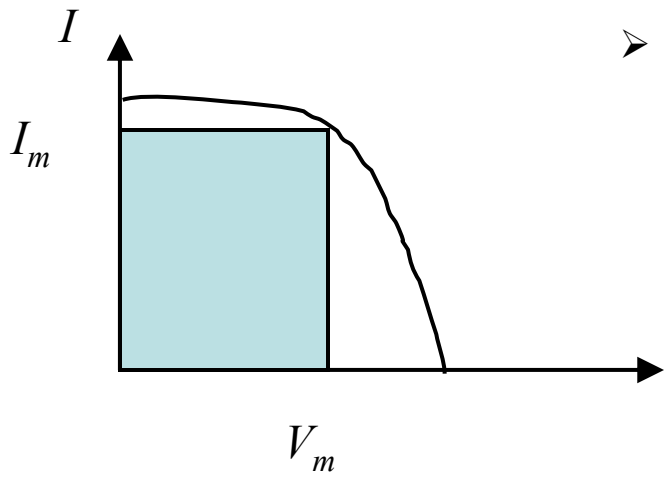
High performance requires

- Minimize light reflection
- Maximize light absorption
- Maximize electron "lifetime" (don't let it fall back to VB)
- Get electrons out of cell with minimal resistance

Basic Parameters of the Solar Cell

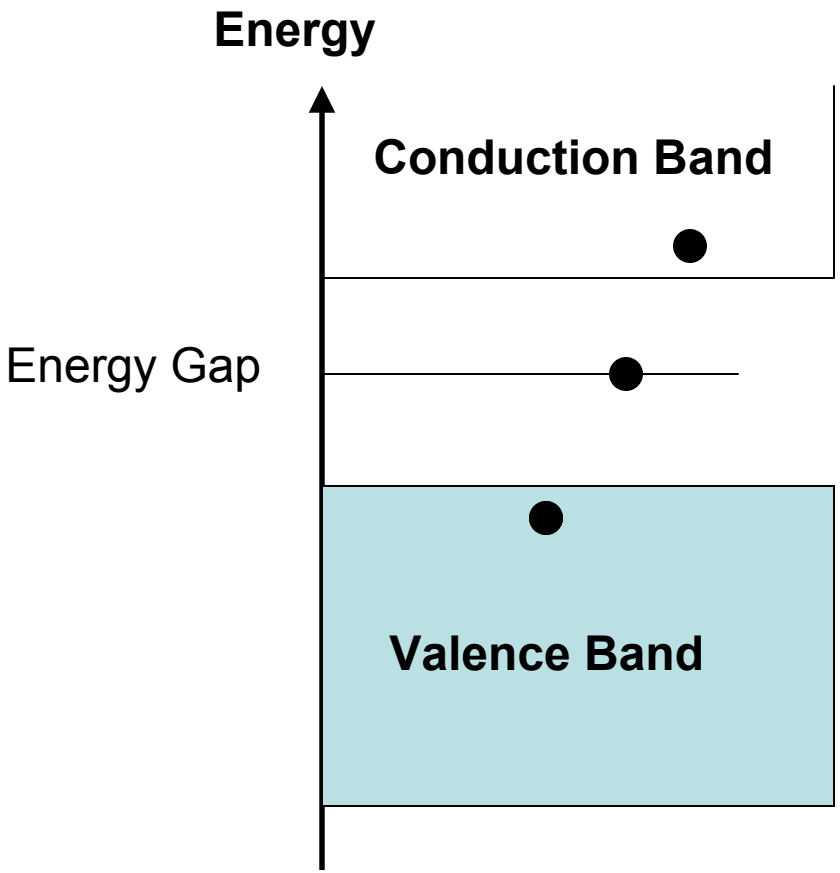
- **Efficiency:** $\eta = \frac{P_m}{E \times A} = \frac{I_m \times V_m}{E \times A}$

  - P_m is the maximum power output of the cell
  - E is the irradiance on the cell under standard conditions (1000W/m^2)
  - A is the area of the cell



- ***IV* Characteristic**
  - I_m is the current at maximum power
  - V_m is the voltage at maximum power

Effect of material quality on electron "lifetime"



Material imperfections cause electrons to fall back to VB before they are collected and delivered to external circuit

Efficiency is reduced

Defect site

(impurity, grain boundary, surface)

Fabrication of a solar cell

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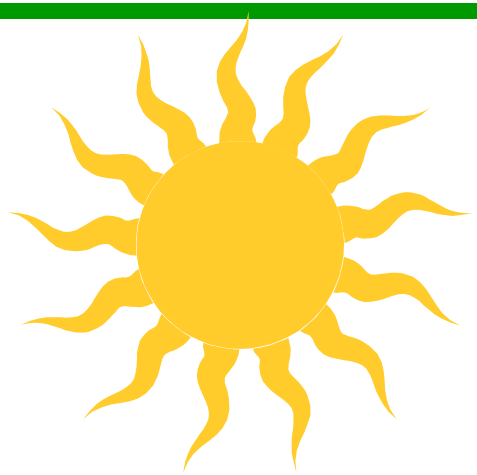
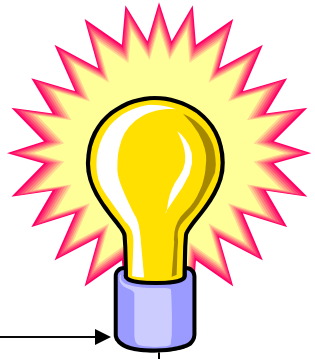
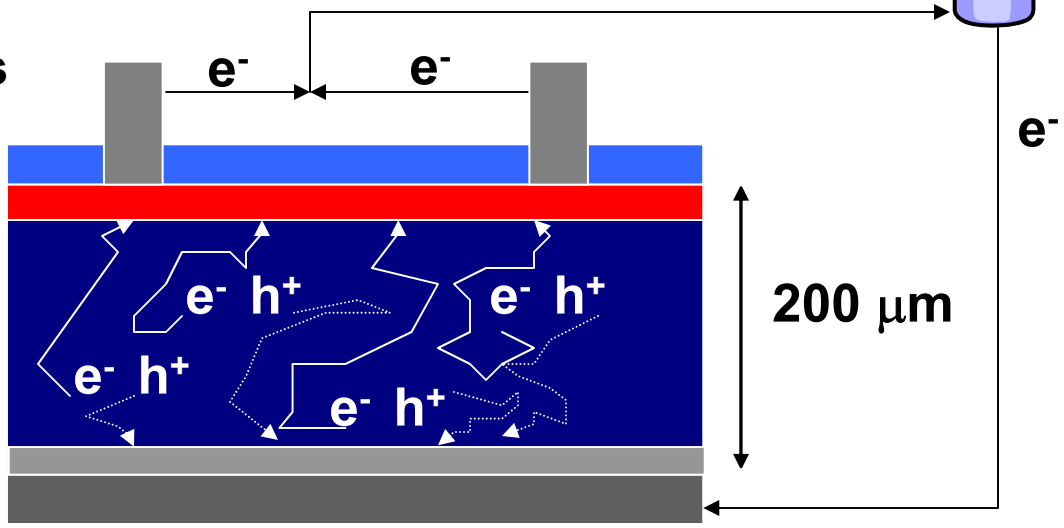
Source:

Professor A. Rohatgi,
Georgia Tech







Common Solar Materials I

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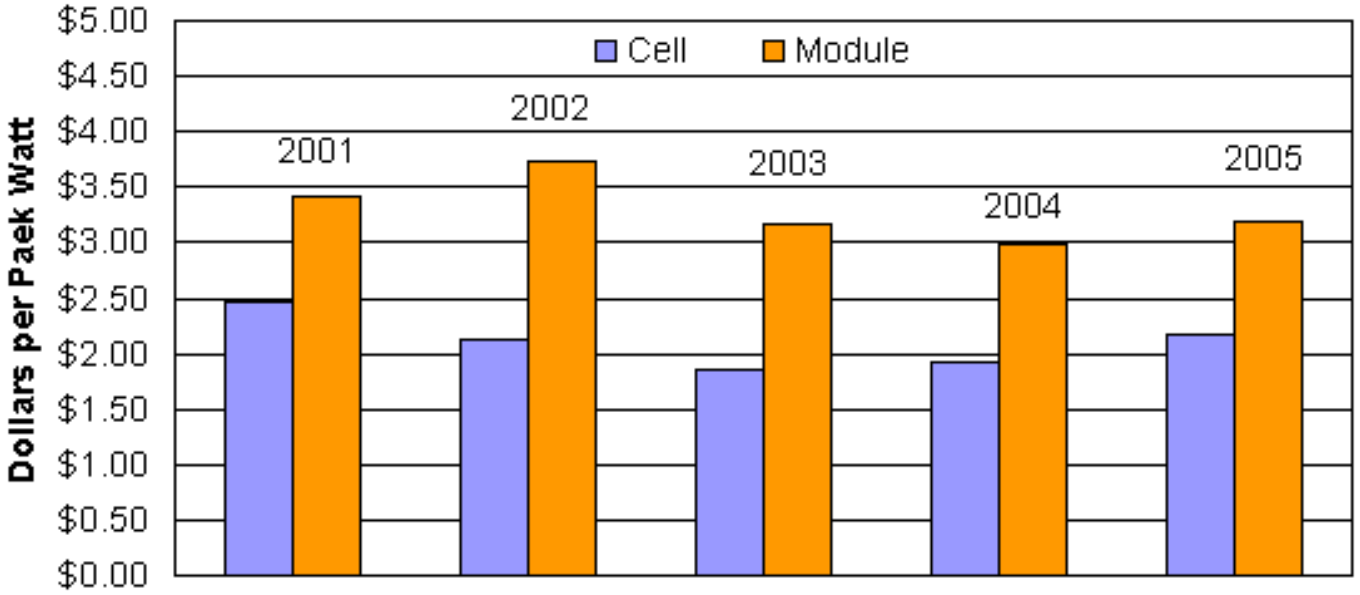
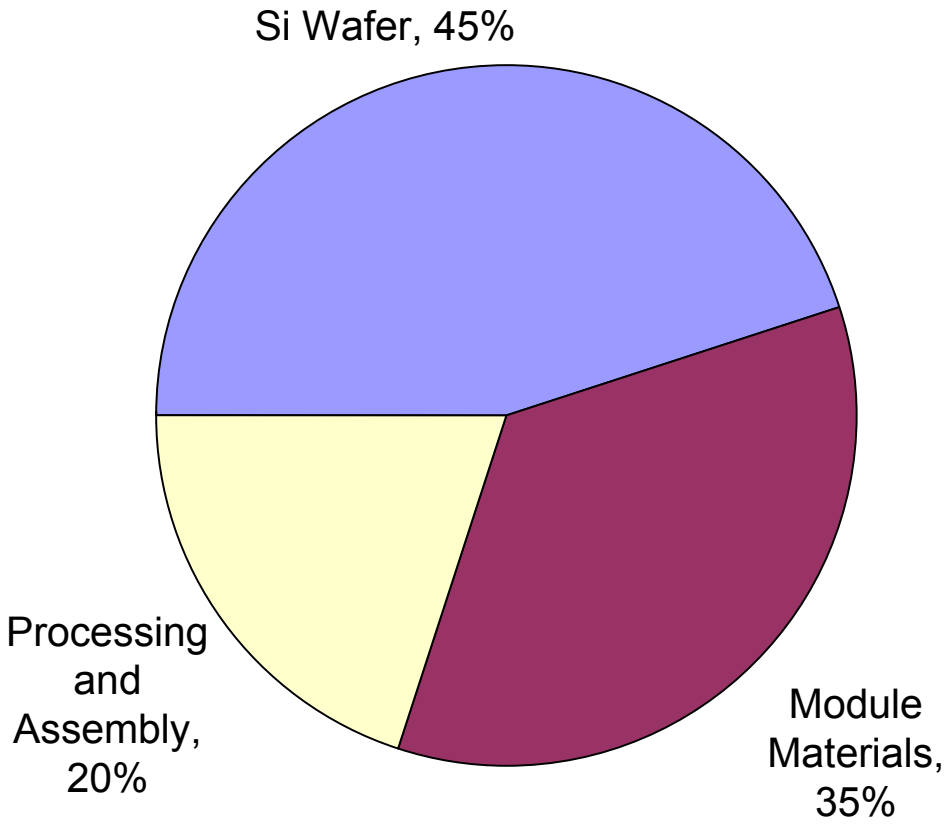
- **Crystalline Silicon**
  - Monocrystalline (single crystal): c-Si 32% m.s.
    - Similar to wafers used for computer chips
    - Expensive to manufacture but provides highest efficiency
    - Manufacturers (SunPower, Sanyo, some BP)
  - Multicrystalline (polycrystalline): mc-Si 45% m.s.
    - Many smaller crystals separated by grain boundaries instead of one large crystal
    - Lower in manufacturing cost and lower efficiency
    - Cast ingots sawn into wafers (Sharp, Q-Cells, Kyocera, BP)
    - Ribbons—eliminates sawing waste (Evergreen, EverQ, Schott)

Recent US Cell and Module Prices



Source: Energy Information Administration, Form EIA-63B, "Annual Photovoltaic Module/Cell Manufacturers Survey," 2005

Cost components for Bulk Si Modules



Common Solar Materials II

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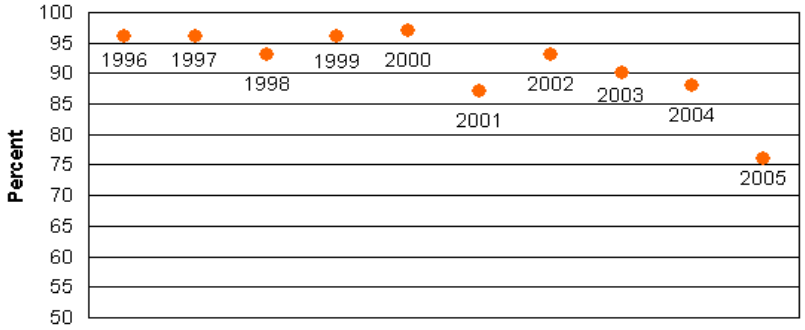
- **Thin Film** **24% m.s.**
  - All seek to reduce material cost by depositing thin films of highly absorbing material on inexpensive substrates such as glass or polymers
  - Generally lower efficiency than bulk Si, but potentially also lower manufacturing cost
  - Some technologies exhibit greater long-term degradation
  - Some substrates are flexible; potentially better compatibility with Building Integrated PV (BIPV)
  - Amorphous Silicon (Uni-Solar)
  - Crystalline Silicon on Glass (CSG-Solar)
  - CIGS- Copper Indium Gallium Diselenide (Daystar, Nanosolar)

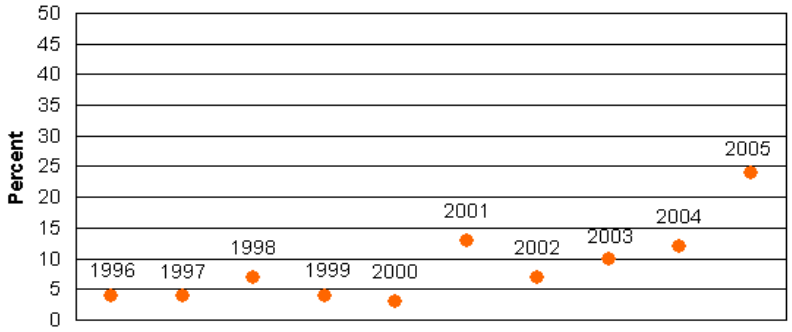
Bulk Si vs. Thin Film US Market Share

Bulk Si

(c-Si, mc-Si)



Thin Film



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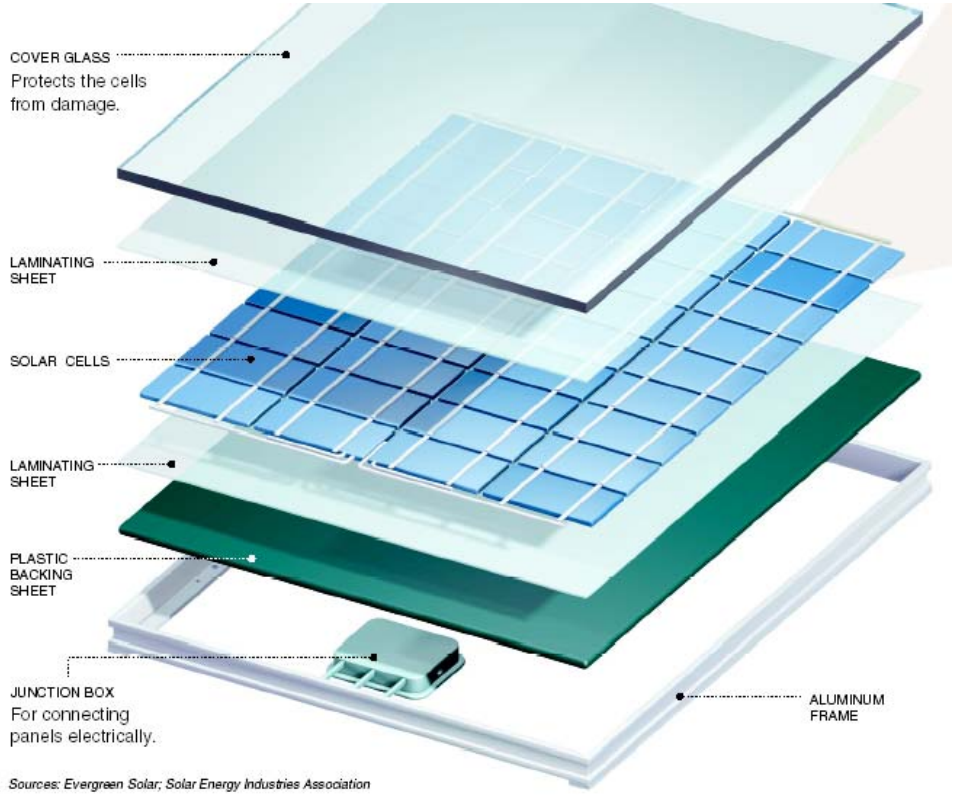
Module Fabrication



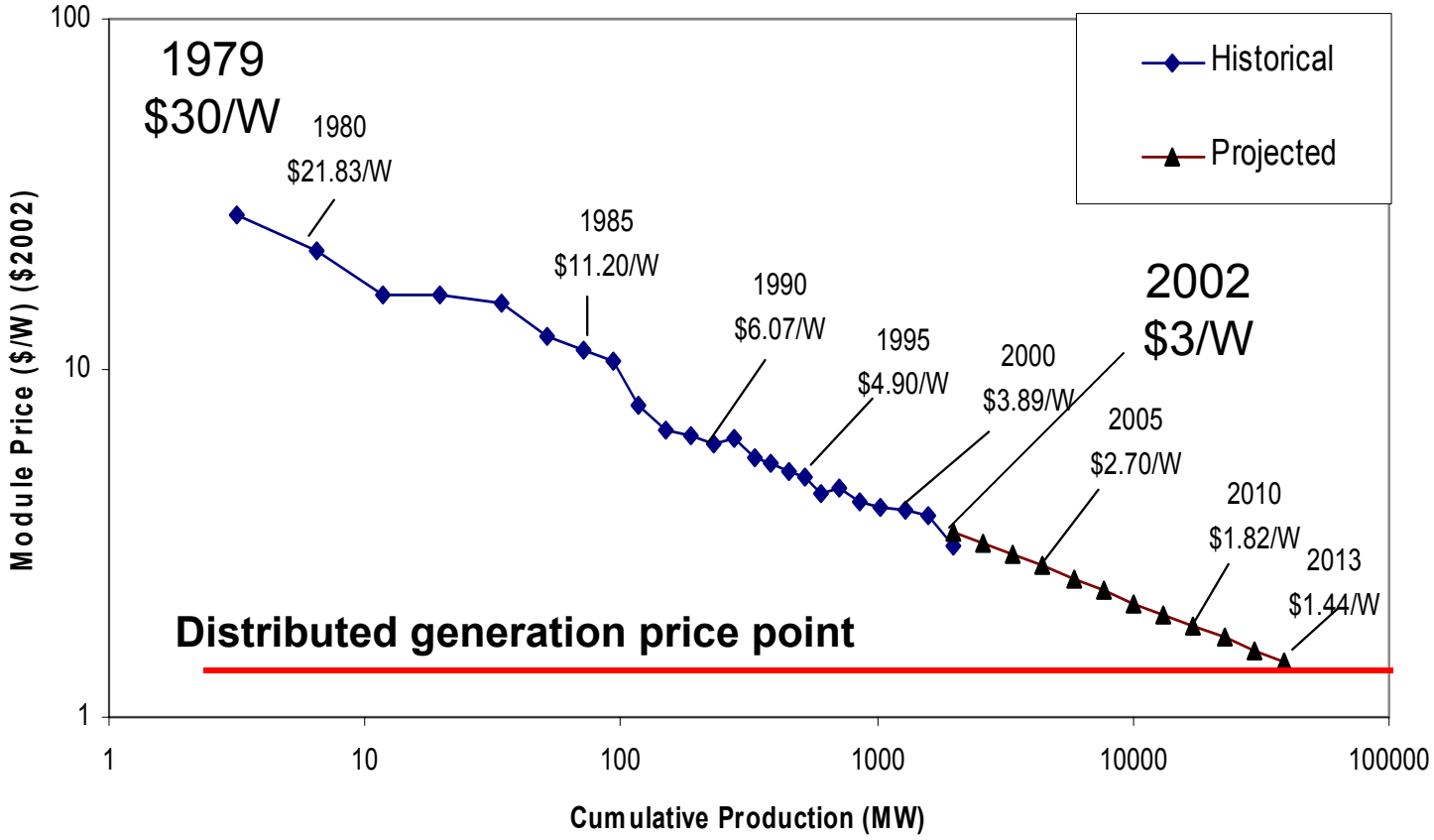
Sources: Evergreen Solar; Solar Energy Industries Association

- **Module Efficiency**
  - **Defined and measured the same as cell efficiency**
  - **Typically 1.5-2% (abs.) lower than cell efficiency (cells at 14.5% yield module at 13%)**

Flatroof Installation

- **Cost breakdown**
  - **Modules $3/Wp**
  - **Balance of systems $3-4/Wp**
  - **Higher efficiency modules reduce BOS costs**

Projecting Future Module Price Trends



Source: Dr. Richard Swanson's presentation to Austin Clean Energy Seminar, 2003

Summary

- Solar photovoltaic power offers a source of renewable energy, reducing dependence on fossil fuels
- Cost reduction is the key to growth of the industry
- Experience curve based on historical data provide reason to expect significant further cost reduction
- Photovoltaic power is a key part of an overall energy strategy including conservation and renewable generation

Back Up Slides

Yachiyo High School, Japan

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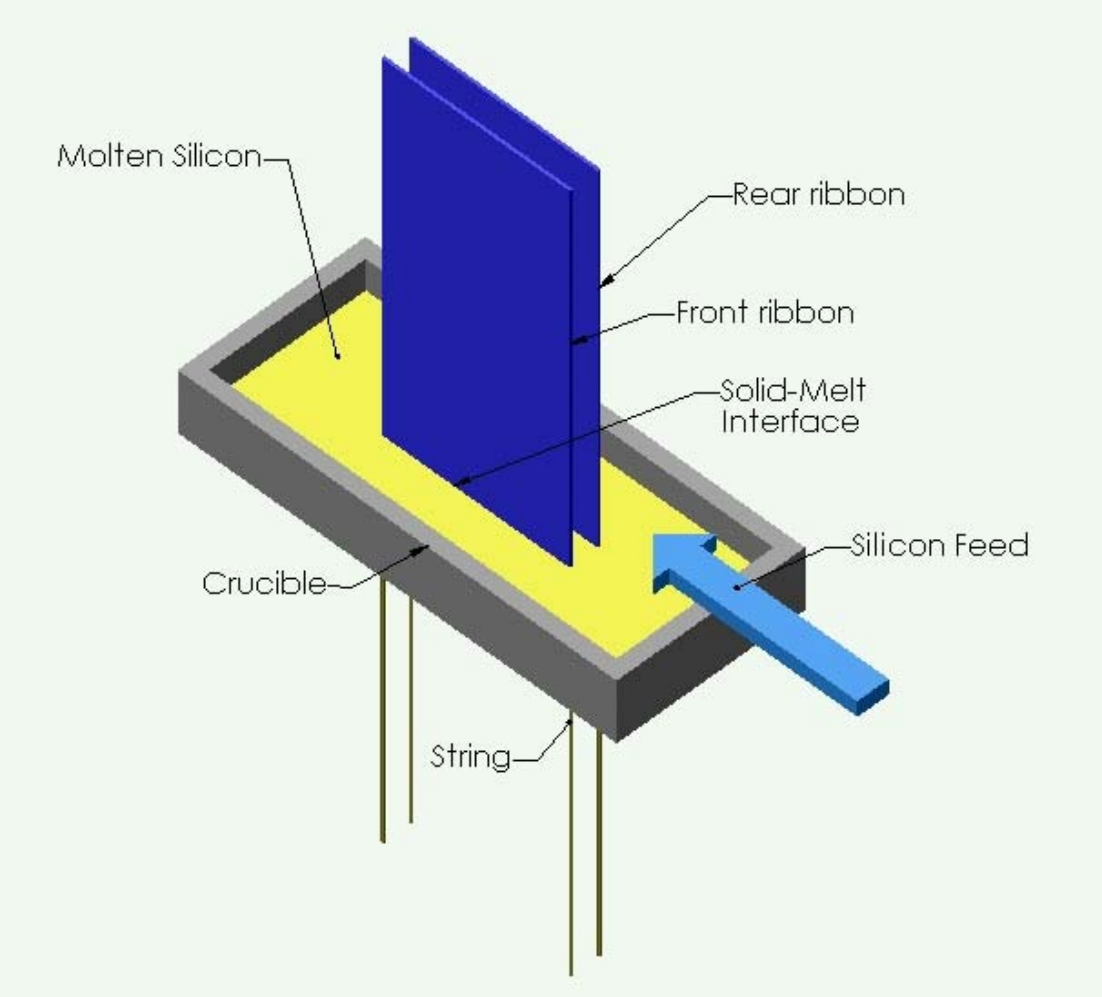
Evergreen modules installed at Japanese site

String Ribbon Growth



Evergreen Crystal Growth

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String Ribbon

Spruce Module

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SPRUCE LINE™ PHOTOVOLTAIC MODULES

SUPERIOR PERFORMANCE

- **Maximum power up to 4% above rated, minimum power only 2% below rated**
- Anti-reflection cover glass delivers more energy
- Power calibrated by three renowned independent tests laboratories

EXTREME DURABILITY

- **Backed by a 25 year limited power warranty; 2 year workmanship warranty***
- A rigid, double walled, deep frame with integrated water drainage holes
- Crimped frame corners – no screws to ever come loose
- Sealed junction box never needs field maintenance

LEADING ENVIRONMENTAL CREDENTIALS

- Low energy – an energy payback time as rapid as 18 months, up to 40% faster than other leading crystalline technologies
- Low carbon – only 30g of carbon dioxide emissions per equivalent kWh of electricity generated, up to 33% less than other leading crystalline technologies
- Low lead – use of lead-free solder for all String Ribbon solar cell inter-connections

CUSTOMER FRIENDLY PACKAGING

- **New bulk packaging eliminates cardboard boxes and minimizes waste**
- Horizontal stacking makes handling of modules easier in the field
- Fully tested to ISTA** standards – the world leader in performance tests for packaged goods

GLOBALLY QUALIFIED

- Certified to the new, stringent IEC 61215 Edition 2 design standard
- Maximum UL system voltage rating 600V
- UL, cUL and CEC Listed
- Fire Safety Class C Rated

ABOUT EVERGREEN SOLAR

Producing our own wafers, cells and modules "under one roof" assures that the highest quality components go into every one of our panels. And since they are made with String Ribbon™ technology, our panels take advantage of one of the newest, fastest growing manufacturing processes in the world.

Evergreen Solar is a publicly listed (NASDAQ) company with over 10 years experience in the solar industry. Our commitment to solar energy is matched only by our commitment to our customers. If you want the best in solar, make the pure choice…Evergreen Solar panels.